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# X-ray Measurements of Highly Charged Europium

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**Abstract.** We present spectroscopic measurements of the M-shell emission of highly charged europium performed at the Livermore SuperEBIT electron beam ion trap facility using the EBIT Calorimeter Spectrometer (ECS). There is significant blending among the emission lines from the different charge states but despite the complexity of the observed spectra we have successfully identified the ten brightest  $n = 4 \rightarrow 3$  transitions from sodium-like  $\text{Eu}^{52+}$  utilizing the Flexible Atomic Code (FAC). We find that the difference between the calculated and measured transition energies for these ten  $\text{Eu}^{52+}$  lines does not exceed 3 eV. In fact, for four of the identified lines we find agreement within the measured uncertainties. Additional comparison with semi-empirical transition-energy predictions for sodium-like ions from laser-generated plasmas is included and shows that overall the semi-empirical predicted values for the transition energies are slightly higher than the measured values, while the FAC values that didn't agree with the measured transition energies are almost 1 eV lower than the measured values.

## 1. Introduction

M-shell emission from highly charged ions has been observed in a variety of different laboratory and astrophysical plasma sources, spanning a wide range of densities and temperatures. The complexity of the spectra originating from the  $4 \rightarrow 3$  transitions of ions that have a partially filled M-shell makes it difficult to utilize M-shell spectroscopy for measurements of plasma parameters, such as electron and ion temperatures, electron densities, and the charge state distribution, respectively [1]. The richness of the M-shell spectra of highly charged ions opens the window on radiative cooling of high-temperature low- $Z$  plasmas by introducing high- $Z$  impurities. For example, using tungsten coated tiles in the divertor region of tokamaks significantly reduces the temperature of the plasma in the divertor region and, thus, extends the lifespan of the walls in the tokamak vessel [2, 3]. In contrast, for indirectly driven ICF plasmas the presence of M-shell emission from laser-heated high- $Z$  hohlraum walls is an unwanted side effect. As the X-ray conversion efficiency significantly increases with the  $Z$  of the hohlraum material, so does the energy of M-shell radiation. The few-keV X rays are hard enough to penetrate the capsule and preheat the fuel which leads to a decrease in the achievable velocity of the imploding capsule. In both cases, detailed spectroscopic measurements are needed in order to quantitatively assess the impact of the M-shell emission on radiative cooling and fuel preheat, respectively. Such detailed studies of the M-shell spectra also pave the way for a reliable utilization of this emission regime as a plasma diagnostic tool.

The Na-like iso-electronic sequence is the simplest of the M-shell ions and has already received some experimental and theoretical attention. In most cases, however, the object of interest is the  $3p_{3/2} \rightarrow 3s_{1/2}$  resonance transition of the sodium like ions and not the  $4 \rightarrow 3$  transitions.

Interestingly, a comparison of transition energy measurements of this intra-M-shell resonance line in Na-like ions obtained from laser-produced plasmas versus accelerators and ion traps indicates a systematic difference between these two experimental approaches to measure M-shell emission. In particular, spectroscopic measurements on laser-produced plasmas involving elements as high as Gd ( $Z=64$ ) have featured a deviation from theory toward shorter wavelengths [4], while high- $Z$  measurements ( $Z \geq 78$ ) on accelerators and ion traps have yielded wavelengths that are longer than semi-empirical predictions based on measurements of sodium-like ions with  $Z \geq 50$  [5, 6, 7, 8]. In order to overlap in  $Z$  with the laser-produced plasma data, we have performed measurements at the Livermore high-energy electron beam ion trap SuperEBIT of the  $3p_{3/2} \rightarrow 3s_{1/2}$  resonance transition in sodium-like  $\text{Eu}^{52+}$  [9]. Here, we present measurements of the  $n = 4 \rightarrow 3$  transitions that we made concurrently in the X-ray region utilizing a cryogenic microcalorimeter as the energy-dispersive detector.

## 2. Experimental Setup

The spectroscopic measurements were performed at the SuperEBIT facility [10, 11, 12] utilizing the EBIT Calorimeter Spectrometer (ECS) [13, 14]. For obtaining the M-shell spectra of highly charged europium, the high-energy SuperEBIT was operated at rather low beam energies, i.e., near 10 keV.

The core feature of the ECS is a pixel array, made of HgTe absorbers, which is cooled to 60 mK. The heat generated by absorption of X rays in the HgTe absorbers is being measured by an intrinsic thermometer. The array contains two types of absorbers that are sensitive to low- and high-energy X rays, respectively. Thus, the ECS can be used to detect X rays in the 0.1 to 100 keV range [15, 16], with a line width (in the low-energy range) of a few eV.

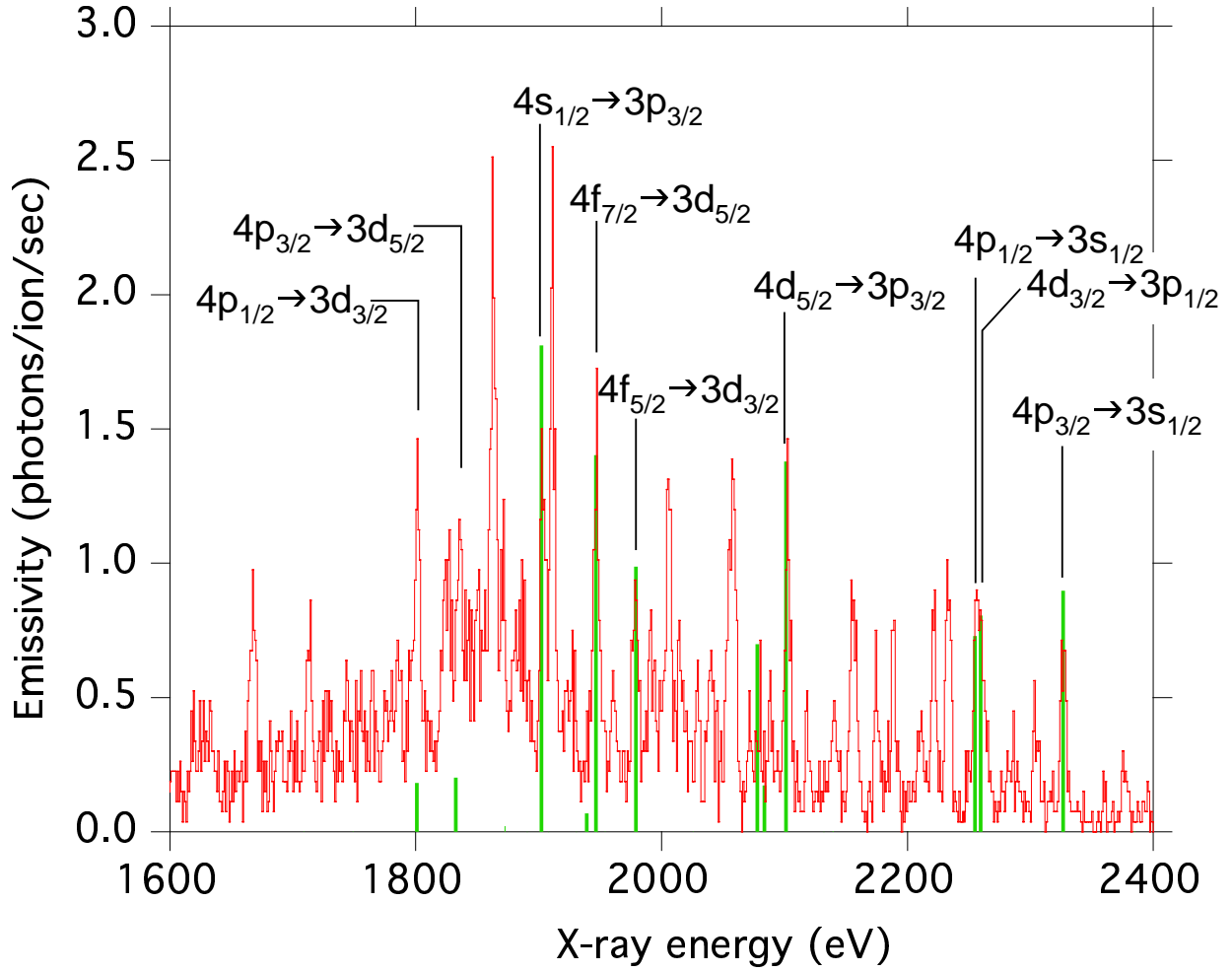
Europium injection into SuperEBIT required the development of a new injection scheme, because europium cannot readily be machined, as it tends to combust in air. For the measurements, we utilized the fact that its vapor pressure is rather high when the material is heated to about 300 °C [17].

## 3. Measurements and Results

A spectrum of the  $4 \rightarrow 3$  emission array of europium obtained with the ECS is shown in Fig. 1. The spectrum exhibits a multitude of (often blended) lines, as is readily seen from the figure. A benefit of the energy-dispersive detection is the observation of whole transition arrays, which gives a wider range and offers opportunities for cross-checks to the ensuing spectrum analysis.

Despite the complexity of the measured spectrum and the significant blending among the emission lines from the different charge states, we were able to identify the ten brightest lines emitted by Na-like  $\text{Eu}^{52+}$ . A series of measurements with varying electron beam energy was conducted to observe the change in the emission spectra as a function of charge state distribution in the ion trap which subsequently allowed us to perform a coarse identification of the Na-like  $\text{Eu}^{52+}$  emission. The final identification of the observed transitions was done by comparing the measured lines with calculations using the Flexible Atomic Code [18, 19]. Figure 1 shows an overlap of the measured spectrum with the FAC calculations and the obtained values are listed in Table 1.

The data set presented in Table 1 show that for most transitions the energy values obtained with FAC are about 1 eV lower than the semi-empirical predictions by Seely *et al* [4] and that the measured values are in between the two predictions. In particular, four of the ten identified lines show agreement with the FAC calculations, and three of the ten lines agree with the semi-empirical predictions by Seely *et al*.



**Figure 1.** M-shell emission spectrum,  $4 \rightarrow 3$  transitions, from highly charged europium. The measured spectrum (solid, red trace) was obtained using the EBIT Calorimeter Spectrometer (ECS). The green bars indicate the result obtained with the Flexible Atomic Code (FAC) [18] and the transition labels indicate the lines that we have identified as belonging to Na-like  $\text{Eu}^{52+}$ . The vertical axis is the output of the FAC calculations; the data have been scaled for display.

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**Table 1.** Measured and calculated values for the energies of the  $n = 4 \rightarrow 3$  transitions in Na-like  $\text{Eu}^{52+}$ . The “ECS” column shows the values measured at the Livermore SuperEBIT with the EBIT Calorimeter Spectrometer (ECS), the column “FAC” lists the calculated values using the Flexible Atomic Code (FAC)[18], and the “Seely” values are from semi-empirical calculations [4]. The three right columns show the difference between the measured and calculated values. All values are in eV.

Transition	Measured	Calculated		Difference		
	ECS	FAC	Seely	Seely - FAC	ECS - Seely	ECS - FAC
$4p_{1/2} \rightarrow 3d_{3/2}$	1801.4(5)	1800.75	1750.07	-50.68	51.4	0.7
$4p_{3/2} \rightarrow 3d_{5/2}$	1836.0(5)	1832.78	1832.89	0.11	3.1	3.2
$4s_{1/2} \rightarrow 3p_{3/2}$	1902.7(5)	1902.00	1903.59	1.59	-0.9	0.7
$4f_{7/2} \rightarrow 3d_{5/2}$	1946.8(5)	1946.34	1947.79	1.45	-1.0	0.5
$4f_{5/2} \rightarrow 3d_{3/2}$	1978.8(5)	1978.87	1980.56	1.69	-1.8	-0.1
$4s_{1/2} \rightarrow 3p_{1/2}$	2080.1(5)	2077.76	2079.40	1.64	0.7	2.3
$4d_{5/2} \rightarrow 3p_{3/2}$	2102.0(5)	2100.97	2102.14	1.17	-0.1	1.0
$4p_{1/2} \rightarrow 3s_{1/2}$	2255.2(10)	2254.95	2255.48	0.53	-0.3	0.2
$4d_{3/2} \rightarrow 3p_{1/2}$	2260.9(10)	2259.38	2260.01	0.63	0.9	1.5
$4p_{3/2} \rightarrow 3s_{1/2}$	2326.5(5)	2326.71	2327.47	0.76	-1.0	-0.2

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